

# Beyond the single species climate envelope: a multifaceted approach to mapping climate change vulnerability

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**Abstract.** Federal land management agencies and conservation organizations have begun incorporating climate change vulnerability assessments (CCVAs) as an important component in the management and conservation of landscapes. It is often a challenge to translate that knowledge into management plans and actions, even when research infers species risk. Predictive maps can improve current CCVAs and assist in quantifying and visualizing species climate change vulnerability across large areas. We assessed the climate change risk for Greater Sage-Grouse (*Centrocercus urophasianus*; sage-grouse) habitat at two spatial scales in Utah and Nevada. At the local scale, multiple species climate envelopes were evaluated with additional stressors (fire, conifer encroachment, invasive grass, and human impact) to create risk maps for mesic (Strawberry) and xeric (Sheeprock) sage-grouse landscapes in Utah. Both landscapes were predicted to be at risk, but Sheeprock was found to be at higher risk due to future climate change implications coupled with additional habitat-degrading stressors. By using models, we are able to integrate complex interactions, and visualize the distribution of risk across broad spatial scales, providing land managers and researchers a valuable tool for CCVA and action plans.

**Key words:** *Centrocercus urophasianus*; climate change vulnerability; climate envelope; sage-grouse.

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## INTRODUCTION

### Greater Sage-Grouse

Greater Sage-Grouse (*Centrocercus urophasianus*; hereafter referred to as sage-grouse) are sagebrush (*Artemisia* spp.) obligates found in portions of the Great Basin, Pacific Northwest, Colorado Plateau, Wyoming Basin, and Northwestern Great Plains Ecoregions where vegetation is dominated by sagebrush steppe ecosystems (Braun et al. 1977, Holloran and Anderson 2005). Despite the broad distribution, sage-grouse habitats have been significantly reduced and/or degraded across their range (Schroeder et al. 2004, Beck et al. 2003). For example, Noss et al. (1995) identified sagebrush

ecosystems as one of the most imperiled ecosystems in North America. This loss and degradation has been attributed to the rapid system changes, as a result of invasive species, wildland fire, and anthropogenic disturbances (USFWS 2010). Sage-grouse are an ideal landscape species for climate change risk assessment and mapping. This is due to their broad distribution, specific habitat requirements, recent habitat declines, and an ever growing body of peer-reviewed literature. A comprehensive review of sage-grouse and their habitats can be found in Knick and Connelly (2011), Connelly et al. (2011), and Crawford et al. (2004).

Within sagebrush ecosystems, sage-grouse often function as an umbrella species for a wide

variety of other organisms (Rowland et al. 2006, Hanser and Knick 2011, Gamo et al. 2013). As an umbrella species, conservation measures for sage-grouse habitat have been shown to benefit other sagebrush-dependent organisms. In 2010, sage-grouse were considered as a candidate species for listing under the Endangered Species Act by the United States Fish and Wildlife Services (USFWS), primarily due to habitat loss and degradation (USFWS 2010). Improved conservation and management efforts prompted the USFWS, in 2015, to remove sage-grouse from the 2010 warranted listing (USFWS 2015). Regardless of the species' current status, many of the threats to sage-grouse habitat remain and will likely continue into the future (Miller and Eddleman 2001). The well-documented loss of habitat and the recently observed range-wide population declines (Knick and Connelly 2011) mandate a need for better understanding and management of remaining habitat (Diamond et al. 1989).

#### *Climate change vulnerability*

An understanding of the realities of a changing climate alone does not sufficiently inform researchers and land managers whether a species' overall health and reproduction status will diminish in the future (Williams et al. 2008, Thomas 2010). However, a combination of factors, including exposure, ability to adapt, and sensitivity to change, provides a more complete idea of how a species will cope in the face of future climate variation (Füssel and Klein 2006, Lindner et al. 2010, Dawson et al. 2011). Defining a species' vulnerability to future climate change requires extensive knowledge about the species and its habitat, as well as past, current, and future climate conditions (Williams et al. 2008).

There are a growing number of peer-reviewed climate change vulnerability assessment (CCVA) tools available to assist managers in determining species or habitat vulnerability to climate change (Rahel and Olden 2008, Bagne et al. 2011, Young et al. 2011). These tools primarily incorporate a query-based approach, where expert opinion is used to answer questions regarding various aspects of the target species' physiology, phenology, biotic interactions, and habitat quality. The output of most of these tools is a value or a vulnerability classification. However, one of the challenges in applying these tools is knowing how to

dissect their comprehensive nature and produce predictive maps that apply knowledge as a quantitative tool for land use plans, and resulting management actions. With rapid advancements in remote sensing platforms, computer processors, specialized software, geographic information systems (GIS), and interdisciplinary research (Chambers et al. 2007b, Homer et al. 2015), it has become feasible to translate theory into informative predictive maps and outcomes that can be utilized as tools to visualize and quantify the climate change vulnerability for individual species or habitats across a range of spatial and temporal scales.

One tool that incorporates GIS and remote sensing data is climate envelope mapping. Climate envelopes, or bioclimatic envelopes, are species distribution models built around climate variables, based on Hutchinson's (1957) realized niche theory, the set of environmental conditions where a species is potentially found (Pearson and Dawson 2003). Climate envelopes have been used to predict future changes in the extent and spatial distribution of suitable habitat for a variety of plant and animal species (Green et al. 2008), and provide a first approximation to the potential climate vulnerability (Pearson and Dawson 2003). However, single species climate envelopes do not account for biotic interactions or additional stressors that may be exacerbated by future climate change (e.g., fires, invasive species expansion).

Environmental stressors that are influenced by climate change (directly and indirectly) potentially affect sage-grouse and its habitat's ability to adapt to future climate variations. For example, future fire regimes, anthropogenic land use, and invasive species will be influenced by changing climate (Westerling et al. 2006). These changes can have long-term negative impacts on the extent and connectivity of shrub-steppe habitats, important to sage-grouse and other sagebrush obligates (Flannigan et al. 2000, Davies et al. 2011). Therefore, additional stressors should be included when developing future risk assessment maps.

Our objective was to assess sage-grouse climate change vulnerability at two spatial scales and to create predictive climate change vulnerability maps for sage-grouse habitat at a scale relevant for sage-grouse management. We used two existing sage-grouse Priority Areas for Conservation

(PACs; USFWS 2013) in Utah to demonstrate the utility of mapping climate change vulnerability risk at the local scale. These PACs are in close proximity to each other, but we hypothesized that they would differ in their future habitat suitability based on existing environmental conditions. We predicted that the lower-elevation, more xeric PAC (Sheeprock) would be at a higher risk to climate change vulnerability when compared to a more mesic PAC (Strawberry). This higher risk was hypothesized to be due, in part, to the already drier conditions and climate exacerbating stressors (fire, invasive species, etc.) currently affecting the Sheeprock PAC.

## MATERIALS AND METHODS

### *Study area and spatial scales*

Natural systems characteristically demonstrate unique patterns across a range of spatial and organizational scales (Levin 1992). Scale is always a factor when addressing CCVAs (Pearson and Dawson 2003, Turner et al. 2003, Rowland et al. 2011). As management applications were a primary goal, the spatial scale of the CCVA needed to be broad enough to demonstrate whether phenomena observed were isolated, but concise enough to inform management actions at site-specific scales.

We examined the study area at two spatial scales, the larger being a coarse-scale (subregional), representing a large portion of the total sage-grouse population (Fig. 1). Habitats assessed within the subregional scale were defined by sage-grouse PACs (USFWS 2013) located within Utah and Nevada political boundaries and were further restricted to the ecological units defined by three floristic regions described by Omernik (1987; Central Basin and Range, Wasatch and Uinta Mountains, and Colorado Plateau). The purpose of the subregional scale was to gain insight into individual PACs and their connectivity and juxtaposition within a broader spatial context. Additionally, the subregional scale allowed for a more thorough understanding of how past droughts and future climate changes influence sage-grouse habitat within the local PACs, compared to the surrounding areas. Our second, finer spatial scale was defined by individual PACs (Sheeprock and Strawberry; Fig. 1) found within the previously defined subregion. The local PAC

boundaries were further refined to only include areas that were classified as current sage-grouse habitat (winter, brood, or other) by the Utah Division of Wildlife Resources (UTDWR 2013).

### *CCVA tools (theory)*

Two commonly cited CCVAs were chosen to assess the risk level to sage-grouse and their habitat in the study region and the target PACs. The first was Nature Serve's Climate Change Vulnerability Index (CCVI; Young et al. 2011). The second was the System for Assessing Vulnerability of Species to Climate Change (SAVS; Bagne et al. 2011). These tools have been designed to assist land managers and researchers in assessing risks to species as a result of changing climate. Climate envelope maps and current literature were used to inform both CCVAs. Additional data to complete the CCVI were obtained from Climate Wizard (Girvetz et al. 2009). The authors used the query-based approach implemented by both CCVAs to determine sage-grouse risk at subregional and local scales.

Despite similar input questions, CCVI and SAVS differ in their output style for interpretation. The CCVI gives the overall results and confidence as a written classification that falls into one of six categories: extremely vulnerable, highly vulnerable, moderately vulnerable, presumed stable, increase likely, and insufficient evidence. The SAVS provides a numerical representation as to the vulnerability risks that a species faces under climate change. A vulnerability risk of 0 infers that the environmental conditions required by the species will remain static. A positive number indicates that environmental conditions will change and that these may pose risks that are adverse to the species. A negative number indicates that the environmental conditions required by the species may become more favorable in the future. In addition to an overall vulnerability score, SAVS provides a breakdown between four categories (habitat, physiology, phenology, and biotic interactions), each with a value for risk and a percentage of confidence.

### *Climate exposure*

*Climate envelopes.*—To best capture future sage-grouse vulnerability to climate exposure, we created climate envelopes for sagebrush as well as competing invasive species. The objective of the



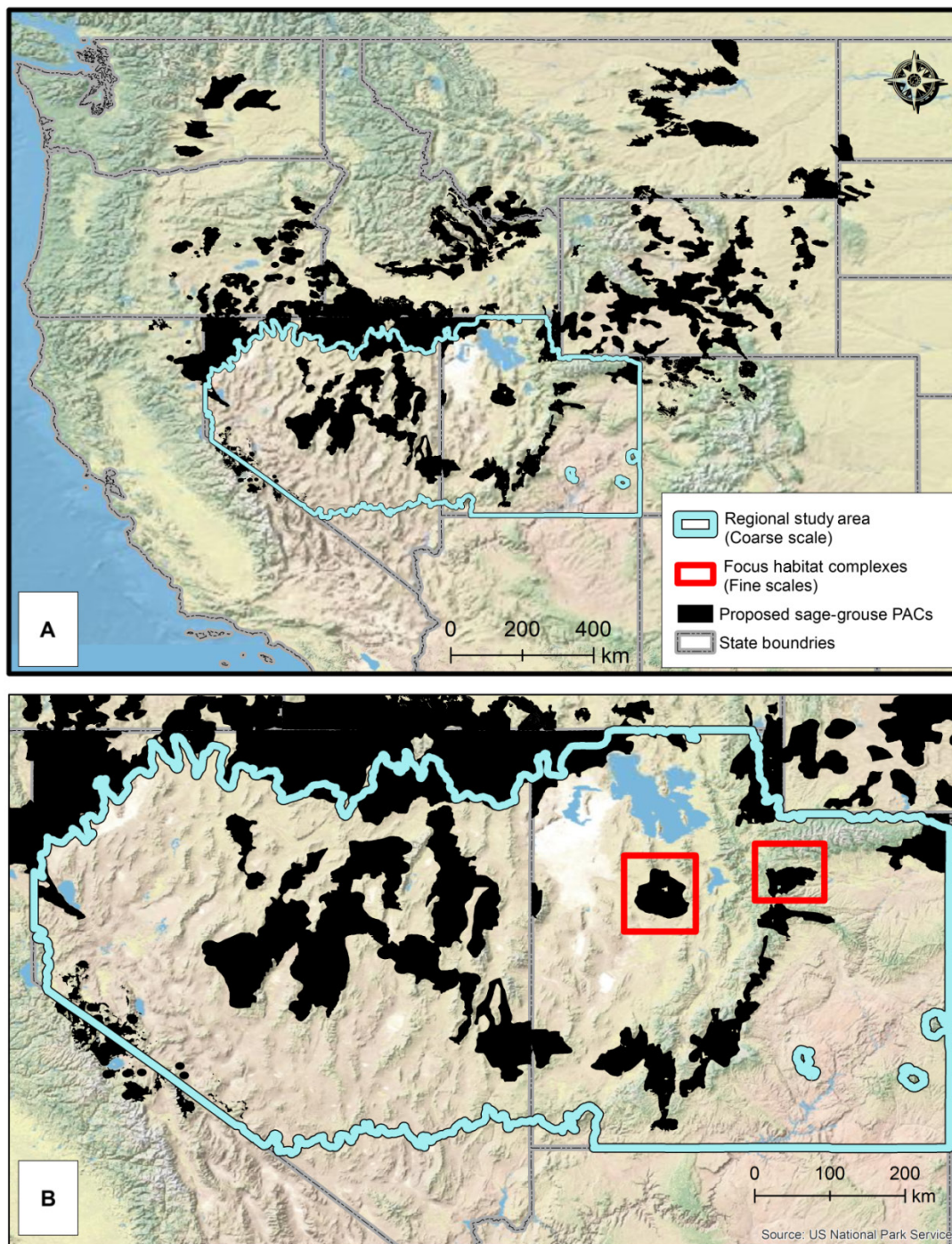


Fig. 1. Study area. (A) The relationship between the subregional study area and the sage-grouse population as a whole. The map does not include sage-grouse found within Canada. (B) The relationship between the subregional component of the study area (cyan) and individual habitat Priority Areas for Conservation (PAC) assessed. The PAC to the west is Sheeprock, and the PAC to the east is Strawberry.

climate envelopes was to predict the spatial distribution of suitable climate for sage-grouse habitats across time. This prediction was based on homoclimate matching, identifying areas with similar climate conditions (Lindenmayer et al. 1991). Twenty-three bioclimatic variables (e.g., mean annual temperature and precipitation) were obtained from the Climate Adaptation Conservation Planning Database for Western North America (Hamann et al. 2013; Box 1). For an in-depth review of the variables, see Hamann et al. (2013). We used these variables in conjunction with the machine learning program, Maxent (version 3.3.3; Phillips et al. 2004, 2006), to create a series of climate envelopes. Maxent has been extensively used in the scientific literature to model species distributions (e.g., Warren and Seifert 2010, Elith et al. 2011, Moreno et al. 2011, Papeş et al. 2012).

All climate envelopes for reference (1961–1990) and future (2050; 2041–2070) conditions were created at the subregional scale. Two key taxa were assessed at this scale: mountain (*Artemisia tridentata* Nutt. ssp. *vaseyana* (Rydb.) Beetle; ARTRV) and Wyoming (*Artemisia tridentata* Nutt. ssp. *wyomingensis* Beetle & Young; ARTRW) big sagebrush. At the local scale, potential invasive conifers (*Pinus edulis* Engelmann; PIED, *P. monophylla* Torrey and Frémont; PIMO and *Juniper osteosperma* (Torrey) Little; JUOS) and the invasive annual grass *Bromus tectorum* L. (BRTE) were added to the assessment (Table 1).

An ensemble of 23 general circulation models, created by Hamann et al. (2013), was used for all future climate models. The A1B emission scenario (considered a moderate emissions outcome) was selected for future predictions. The future A2 emission scenario (high emissions) for mid-century in

### Box 1

Bioclimatic variables were used to create climate envelopes. Data and abbreviations were obtained from Hamann et al. (2013). Data were obtained from <http://www.ualberta.ca/~ahamann/data/climatewna.html>

- Mean annual temperature, MAT (°C)
- Mean temperature of the coldest month, MCMT (°C)
- Mean temperature of the warmest month, MWMT (°C)
- Difference between MCMT and MWMT, as a measure of continentality (°C)
- Mean annual precipitation, MAP (mm)
- Mean summer (May–September) precipitation, MSP (mm)
- Annual heat moisture index, calculated as  $(MAT + 10)/(MAP/1000)$
- Summer heat moisture index, calculated as  $MWMT/(MSP/1000)$
- Degree-days below 0°C
- Degree-days above 5°C
- The number of frost-free days
- The Julian date on which the frost-free period begins
- The Julian date on which the frost-free period ends
- Precipitation as snow (mm)
- Extreme minimum temperature over 30 yr
- Hargreave's reference evaporation
- Hargreave's climatic moisture index
- Hogg's climate moisture index
- Hogg's summer (June–August) climate moisture index
- Winter (December–February) mean temperature (°C)
- Summer (June–August) mean temperature (°C)
- Winter (December–February) precipitation (mm)
- Summer (June–August) precipitation (mm)

Table 1. A list of the climate envelope models made, species abbreviations, and common names.

Climate envelope species	AUC		Overall accuracy		Abbreviation
	Value	<i>n</i>	%	<i>n</i>	
<i>Artemisia tridentata</i> Nutt. ssp. <i>vaseyana</i> (Rydb.) Beetle (mountain big sagebrush)	0.88	892	94	97	ARTRV
<i>Artemisia tridentata</i> Nutt. ssp. <i>wyomingensis</i> Beetle & Young (Wyoming big sagebrush)	0.76	2487	96	102	ARTRW
<i>Pinus edulis</i> Engelm. (two-needle pinyon)	0.93	534	90	50	PIED
<i>Pinus monophylla</i> Torr. & Frém. (single-leaf pinyon)	0.86	1003	89	100	PIMO
<i>Juniperus osteosperma</i> (Torr.) Little (Utah juniper)	0.85	409	84	50	JUOS
<i>Bromus tectorum</i> L. (cheatgrass)	0.85	471	84	50	BRTE

Note: The area under the receiver-operating characteristic curve (ROC) values were used to validate the model creation, and the overall accuracy was used to test the output climate envelope models.

the state of Utah only varied by 0.1°C for mean annual temperature and by 2% for mean annual precipitation (Hamann et al. 2013) compared to A1B, and therefore was not modeled here. In situ data, used in model creation and validation of the climate envelopes, were obtained from the Southwest Regional Gap Analysis Program (GAP) training databases (USGS National Gap Analysis Program, 2004). Model creation was first evaluated using the area under the receiver-operating characteristic curve (ROC), known as the AUC (Fielding and Bell 1997). The AUC values from Maxent range between 1.0, indicating a perfect agreement between the model and the training data, and 0.5 for models that are no better than random. The model outputs were further validated by first applying a 10 percentile threshold (90% of the presence training points located within the predicted area). The 10 percentile threshold was used so the models would be more conservative (Tinoco et al. 2009). Overall accuracy was determined using ground data points that had been randomly withheld from the model creation.

**Drought assessment.**—PACs most impacted by droughts within the last century were evaluated using the Self-Calibrated Palmer Drought Severity Index (SC-PDSI; Alley 1984, Wells et al. 2004). The SC-PDSI is an adaptation on the Palmer Drought Severity Index (PDSI), first introduced by Palmer in 1965. The SC-PDSI works on the same principal as the PDSI by combining water supply and demand with soil moisture to quantify droughts across diverse landscapes; however, the SC-PDSI calibrates the drought index using local climate variables, making the new index more reliable (Wells et al.

2004). The West Wide Drought Tracker data (<http://www.wrcc.dri.edu/wwdt/>) were used to create annual SC-PDSI graphs and layers from 1895 to 2013. The number of continuous drought years was counted within each sage-grouse PAC. Droughts were defined here as a SC-PDSI value of less than −1.0. Droughts were assessed in periods of greater than or equal to three consecutive years and greater than or equal to five consecutive years.

#### *Outside influence on adaptive capacity (local scale only)*

In addition to climate envelopes at local scales, we incorporated several key habitat variables that potentially reduce the resilience of sage-grouse habitat to climate change. These include the following: recent fire history, current conifer encroachment, risk of invasive annual grasses, and current human footprint (Figs. 2 and 3). This is not meant to be an absolute list and could be augmented with additional stressors as data become available. If the suitable climate envelope for sagebrush was lost and these additional stressors were present, then the area was considered to be at a higher risk for sage-grouse loss in the future.

**Fire.**—Within the PACs, fire locations and dates were obtained from the Geospatial Habitat Analysis Laboratory, Brigham Young University, Provo Utah, and are part of the USFS Great Basin Fire Mapping Database project (GBFMD, unpublished data). This data set includes fire locations from state, federal, and private organizations, from 1958 to 2012. With suitable sage-grouse habitat already greatly reduced, any large fire could negatively affect the ability of



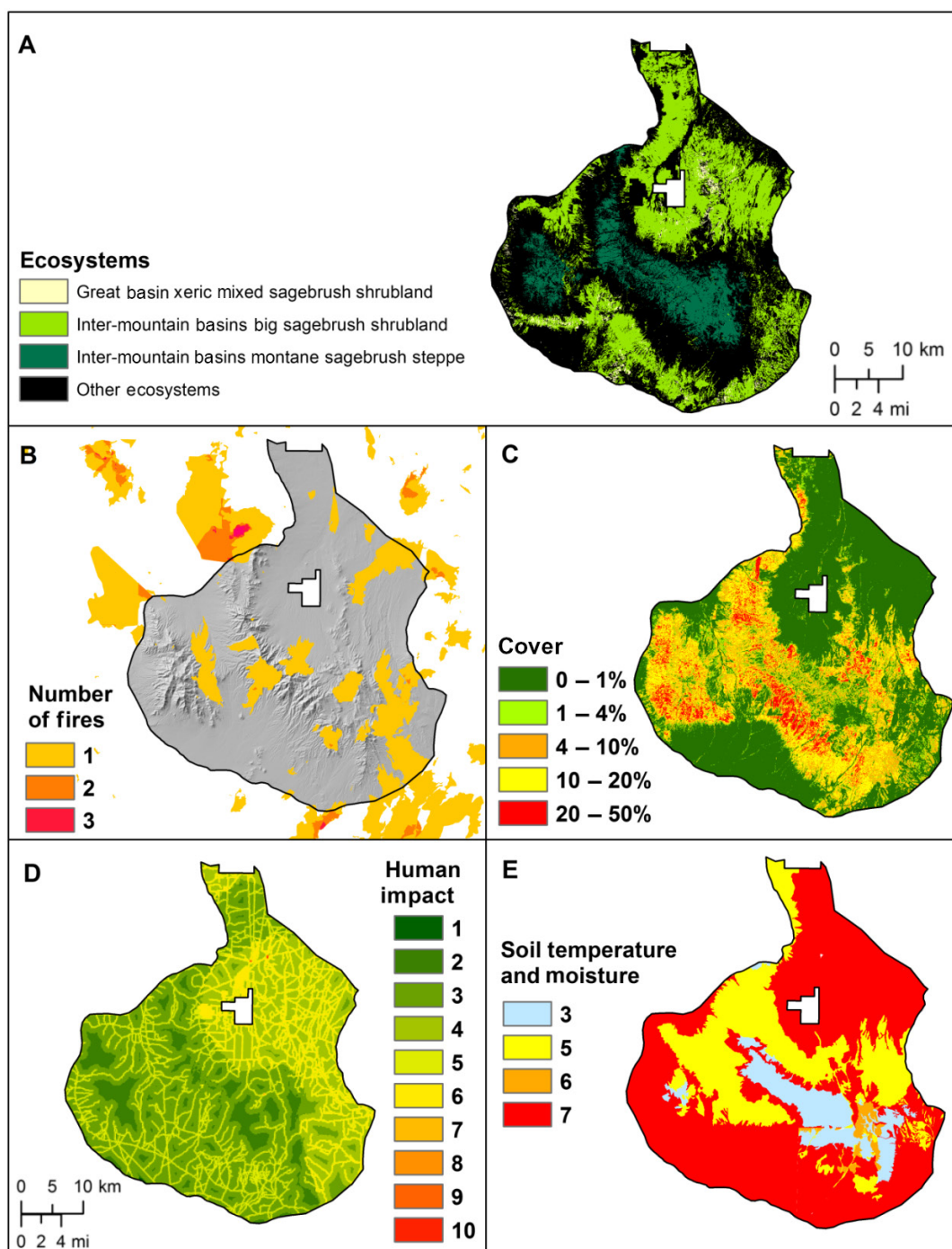


Fig. 2. The Sheeprock Priority Area for Conservation: (A) current sagebrush ecosystems, (B) the number of fires over the past 25 yr, (C) current conifer cover, (D) current human impacts, (E) soil temperature and moisture regimes.

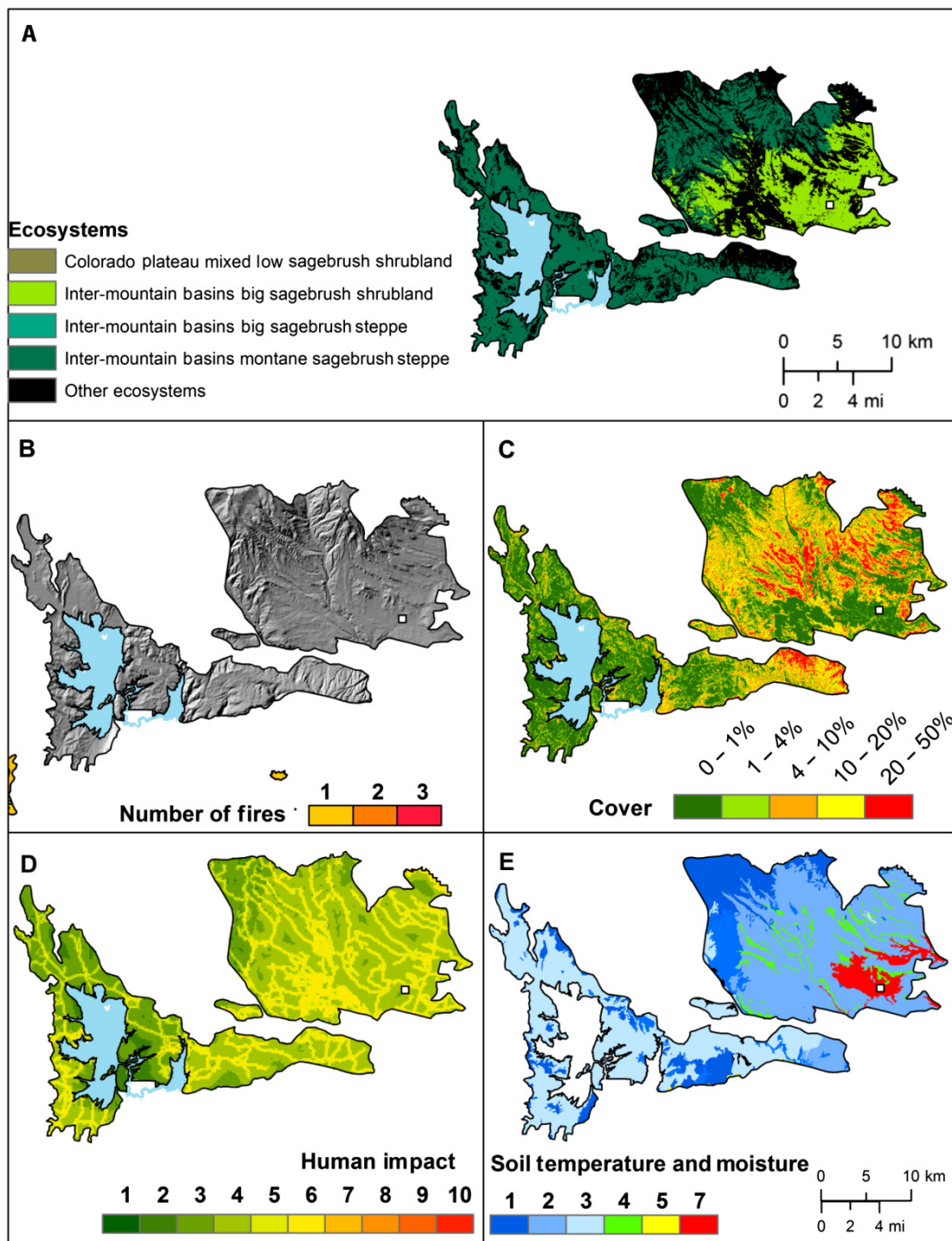


Fig. 3. The Strawberry Priority Area for Conservation: (A) current sagebrush ecosystems, (B) the number of fires over the past 25 yr, (C) current conifer cover, (D) current human impacts, (E) soil temperature and moisture regimes.



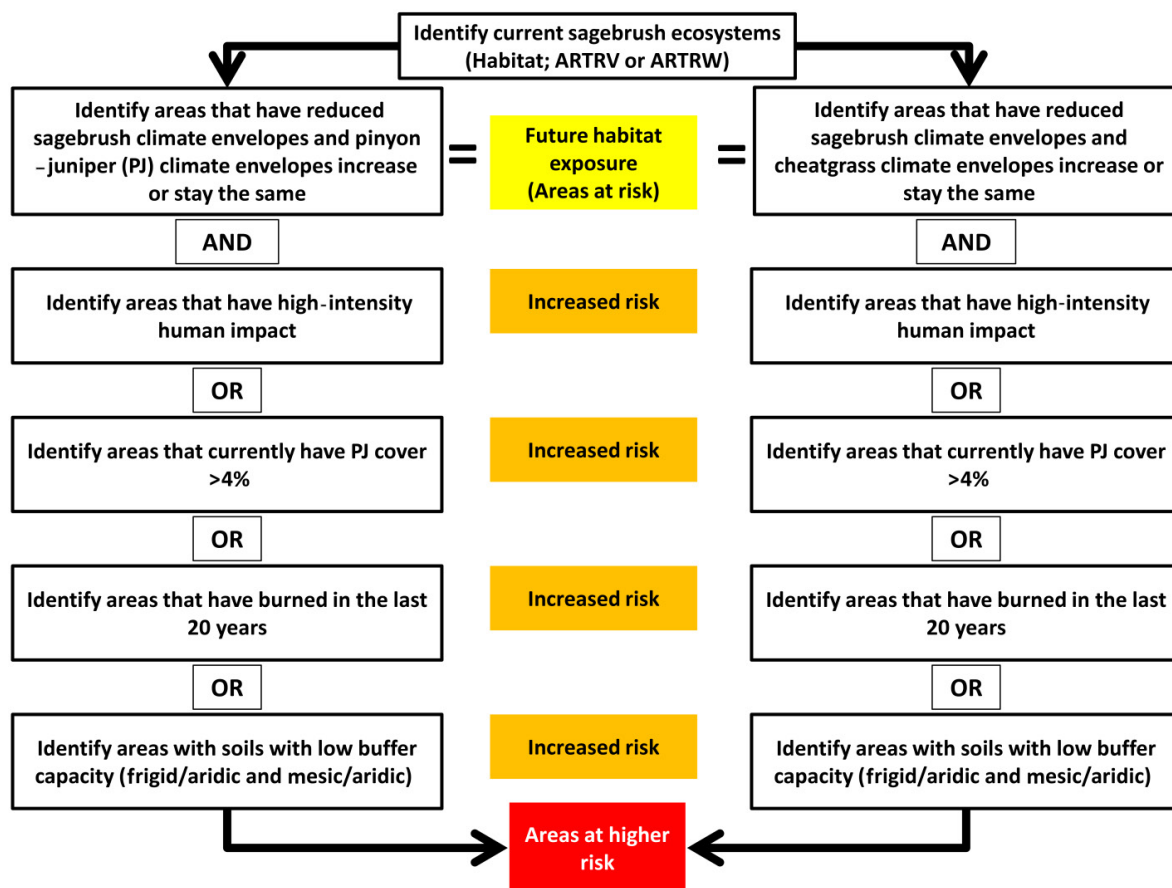


Fig. 4. Workflow for the local-scale risk assessment. Risk is defined here as a reduction in sagebrush climate envelopes and presences of any of the invasive species climate envelopes. Higher risk is defined as risk areas with one or more additional stressors. The model is broken into risks associated with conifers (left side) and risks associated with cheatgrass (right side).

sage-grouse to adapt to and recover from these habitat losses in light of a warming and drying climate. Therefore, we considered any fire from the GBFMD, located inside the PACs within the last 20 yr, an indication of increased risk.

**Conifer encroachment.**—Current conifer encroachment into sagebrush ecosystems was assessed using data obtained from [ftp://ftp.agrc.utah.gov/Imagery/NAIP2011\\_4-band/](ftp://ftp.agrc.utah.gov/Imagery/NAIP2011_4-band/) (Falkowski et al. 2006). Conifer encroachment was classified into five classes based on conifer overstory cover percentage: 0–1, 1–4, 4–10, 10–20, and 20–50%. Areas with cover classes  $\geq 4$ –10% were considered at higher risk (Baruch-Mordo et al. 2013).

**Soils and invasive annual grasses.**—A landscape's resistance to invasion of annual exotic species has been linked to current soil temperature and

moisture regimes (Chambers et al. 2014). A soil temperature and moisture regime layer, generated from the Soil Survey Database (SSURGO; Soil Survey Staff 2014a) and the State Soil Geographic Database (STATSGO; Soil Survey Staff 2014b), was used as a proxy for areas at higher risk for invasive annual grasses (Chambers et al. 2013, 2014). We considered areas at higher risk, if they contained soil moisture and temperature regimes of frigid/aridic (cool dry) or mesic/aridic (warm dry).

**Human impact.**—We used a human footprint model, developed by Leu et al. (2008), to address current human impacts within the sage-grouse PACs. The human footprint model was a combination of three top-down models addressing anthropogenic predator assistance (avian predators, dogs, and cats) as well as four bottom-up

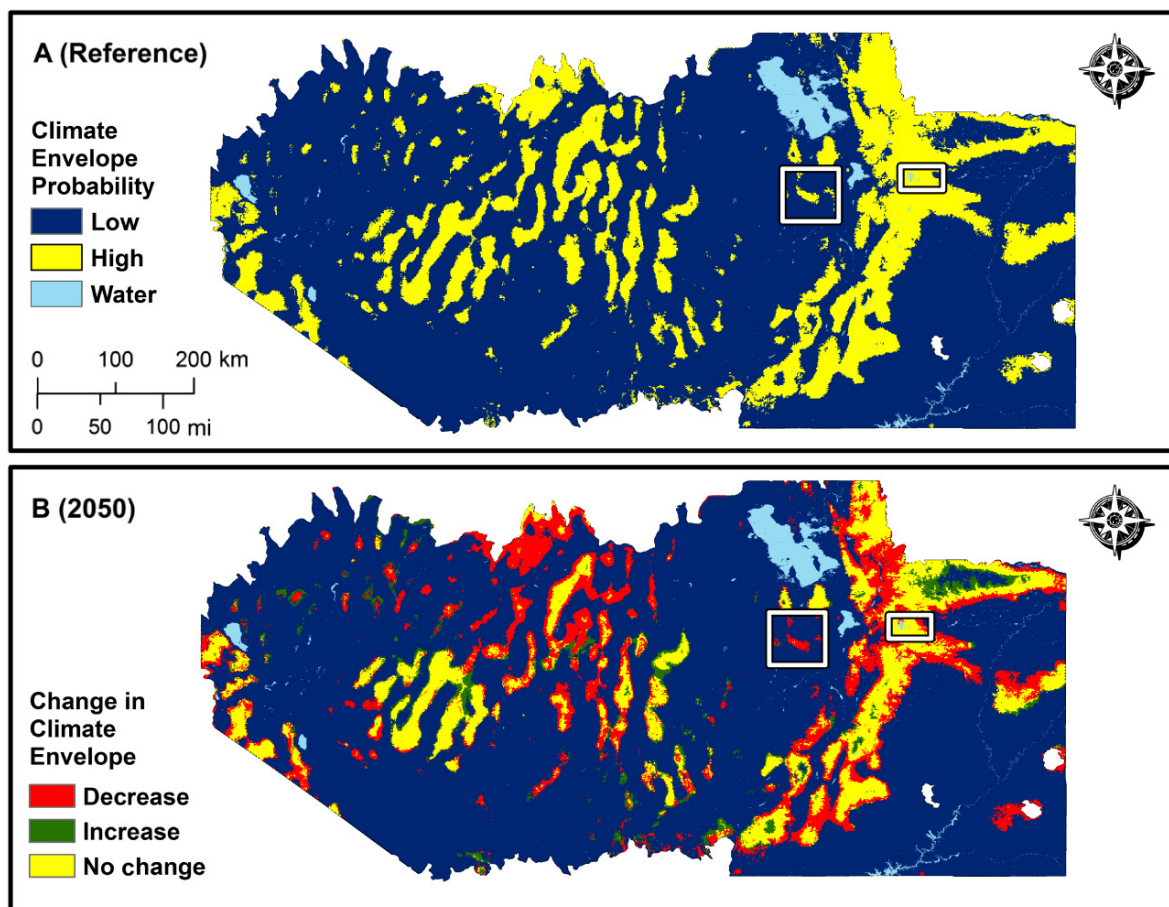


Fig. 5. Predicted climate envelopes for ARTRV-dominated ecosystems (subregion). (A) The predicted reference climate envelope for ARTRV (1961–1990). (B) The predicted change to the ARTRV climate envelope in the absence of competition. The white boxes outline the two local study areas. The box to the west is Sheeprock, and the box to the east is Strawberry.

models (exotic plants, anthropogenic fires, energy extraction, and wild land fragmentation). We used this model due to its inclusive coverage of human impacts, as well as its past use in sage-grouse habitat assessments (Leu and Hanser 2011). The human footprint model was scaled from 1 to 10 with 1 representing the lowest amount of impact and 10, the highest. For visualization, the human impact model results were broken into categories, defined by Leu and Hanser (2011): low impact (1–3), moderate impact (4–6), and high impact (7–10). Impact values  $> 6$  were considered at increased risk.

#### *Risk models (local scale only)*

Once the CCVA tools were used to determine whether the PACs were considered vulnerable

to climate change, we combined data layers to create maps that predicted the climate change vulnerability risk for sage-grouse (Fig. 4). Areas within PACs that contained sagebrush-dominated ecosystems (ARTRW and ARTRV) were first identified. Probability of risk due to climate envelopes alone was assigned for sagebrush components based first upon projected change in sagebrush climate envelopes and invasive species presence. If an area was defined as at risk, it was further evaluated for the presence of additional stressors (fire, conifer encroachment, human impact, or xeric soils). In the event that one or more of these stressors were found in an area defined as at risk, it was upgraded to high risk. To further assist land managers in

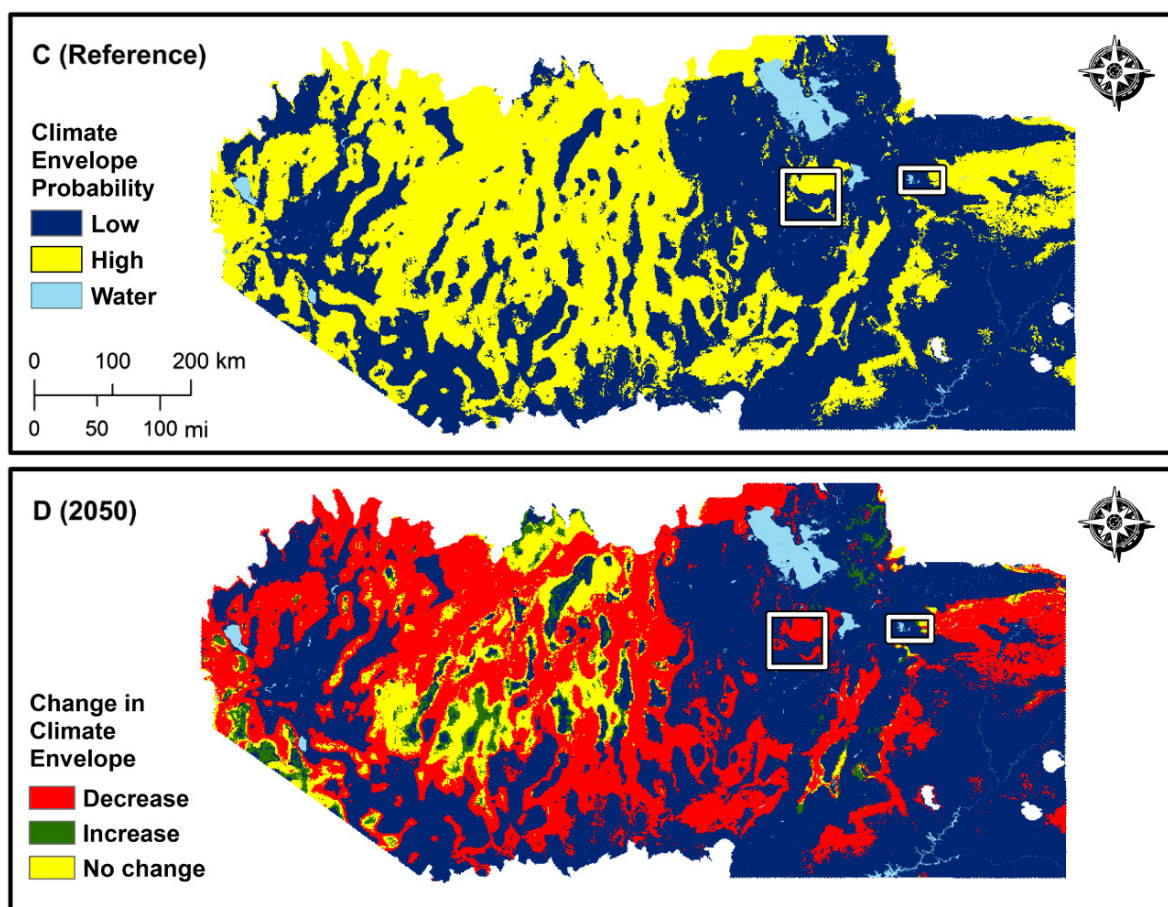


Fig. 6. Predicted climate envelopes for ARTRW-dominated ecosystems (subregion). (A) The predicted reference climate envelope for ARTRW (1961–1990). (B) The predicted change to the ARTRW climate envelope in the absence of competition. The white boxes outline the two local study areas. The box to the west is Sheeprock, and the box to the east is Strawberry.

assessing risk and determining appropriate actions, separate models were made for the two dominant sagebrush ecosystem types (ARTRW and ARTRV). Additionally, for each sagebrush ecosystem type, separate risk models were created for conifer encroachment (JUOS, PIMO, or PIED) and for invasive grass (BRTE). This was carried out due to the different management strategies needed to address conifer encroachment vs. invasive annual grasses.

## RESULTS

### *Climate envelopes*

Two sagebrush ecosystems (ARTRV and ARTRW) currently dominate sage-grouse PACs

at the subregional scale (Figs. 5 and 6). The modeled ARTRV climate envelope had an area under the receiver-operating characteristic curve (AUC) of 0.88 with an overall accuracy of 94% (Table 1). The modeled ARTRW climate envelope had an AUC of 0.76 with an overall accuracy of 96%. Of the two vegetation types, current ARTRW-dominated systems showed the greatest potential for loss of area due to the future predicted climate. The model predicted almost a complete loss of suitable ARTRW climate in the eastern portion of the subregion (Utah) and a substantial loss in the west (Nevada). In contrast, predicted loss for the ARTRV climate envelope was much less. There was some predicted ARTRV climate envelope expansion in areas upslope of the



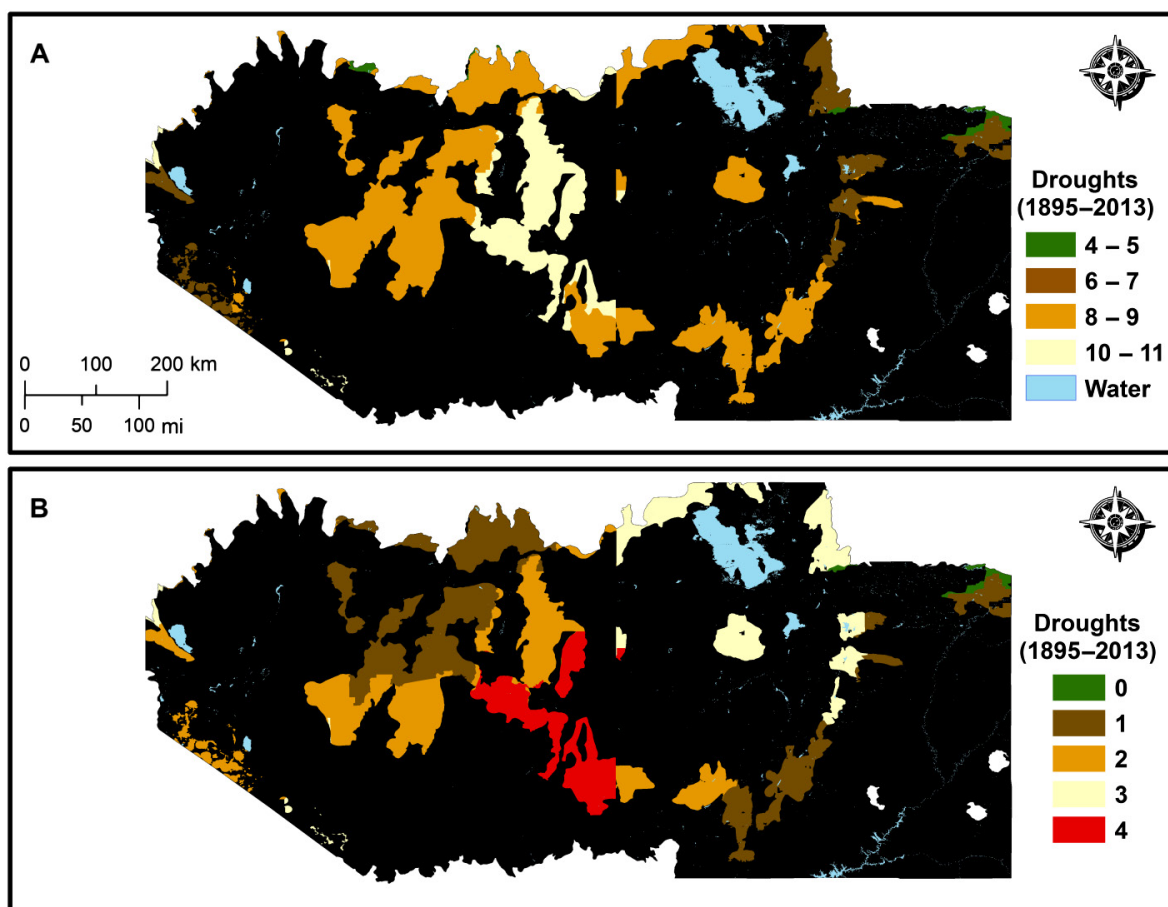


Fig. 7. (A) The number of droughts lasting three or more years between 1895 and 2013 within the sage-grouse Priority Areas for Conservation (PAC). (B) Droughts lasting five or more years.

current distribution, particularly in the northeast portion of Utah (Uintah Mountains). This shift was primarily into areas currently occupied by conifers making expansion unlikely. Overall, both sagebrush ecosystems, and therefore sage-grouse habitat, showed a future decrease in area of suitable climate. A predicted loss of suitable climate may not equate to a loss of that ecosystem; however, it can be seen as an indication of additional stress or susceptibility to loss in the event of a future disturbance.

#### Drought

All PACs in the subregion were exposed to periods of multiyear (3- to 5-year) drought between 1895 and 2013. During this time, drought was most frequent in eastern Nevada and least frequent in northeastern Utah (Fig. 7). Drought may serve as a

means to determine sage-grouse sensitivity and adaptive capacity to a warmer, drier climate. Prolonged droughts in the recent past have coincided with declining sage-grouse populations across much of their range (Connelly et al. 2000).

#### CCVA tools

Although the outcomes of the CCVA tools differed slightly, both found that sage-grouse, across all spatial scales and landscapes assessed, are at risk to climate change. The CCVI scored the subregion and both PACs as extremely vulnerable with very high confidence. The SAVS tool differed slightly between each PAC and the subregion scale. In the SAVS tool, the subregion had an overall vulnerability of 5.45 and an uncertainty of 5%, indicating a climate vulnerability risk for sage-grouse. Habitat was the subfactor

Table 2. System for Assessing Vulnerability of Species to Climate Change (SAVS) output data.

Area	Overall	Habitat	Physiology	Phenology	Biotic interactions
Subregion	5.45/5%	2.74/0%	-1.0/0%	1.25/0%	2.0/20%
Sheeprock	9.09/9%	3.57/0%	1.67/0%	2.50/25%	1.0/20%
Strawberry	4.55/5%	-0.12/0%	0.83/0%	2.5/25%	2.0/0%

Notes: A vulnerability risk of 0 infers that the environmental conditions required by the species will remain static. A positive number indicates that environmental conditions will change and that these may pose risks that are adverse to the species. A negative number indicates that the environmental conditions required by the species may become more favorable in future.

that contributed the most risk, with a score of 2.74 and 0% uncertainty (Table 2).

Using the SAVS tool, Strawberry had an overall vulnerability of 4.55 with an uncertainty of 5%. Biotic interaction (e.g., predation) contributed the most vulnerability within the Strawberry PAC, with a value of 2.0 and 0% uncertainty. Sheeprock, however, had an overall vulnerability of 9.09 with an uncertainty of 9%. The category within Sheeprock that contributed the most risk to vulnerability was habitat, with a value of 3.57 and an uncertainty of 0% (Table 2).

#### Risk models

The Sheeprock future risk models (looking at climate envelopes alone) showed a reduction in the climate envelope for sagebrush for both ARTRV and ARTRW, and a persistence and/or increase in the climate envelopes for conifer (Figs. 8B1 and 9B1) as well as for invasive grass (Figs. 8B2 and 9B2). When the additional stressors were factored in to identify the areas of highest risk, 46% of the PAC was classified as high risk in the ARTRW ecosystems within the conifer encroachment category (Fig. 9C1) and 45% in the invasive grass category (Fig. 9C2). In the ARTRV ecosystems, Sheeprock had 29% high risk in the conifer encroachment category (Fig. 8C1) and 37% in the invasive grass category (Fig. 8C2). Furthermore, areas at highest risk were not geographically isolated and were spread across the entire PAC.

Within ARTRV ecosystems, Strawberry had 14% of the area predicted as high risk (Fig. 10C1). The ARTRV areas, predicted as highest risk in the Strawberry PAC, are located at the interface between sagebrush ecosystems and pinyon and juniper woodlands (Fig. 10C1). The BRTE climate envelope was not present as a risk factor in the Strawberry PAC for current or for future conditions (Figs. 10B2 and 11B2). Strawberry also

showed future reductions in the ARTRW climate envelope and a persistence of and/or increase in a conifer climate envelope (Fig. 11B1). Strawberry PAC had 21% predicted high-risk conifer encroachment areas, associated with ARTRW climate envelope loss and one or more additional stressors (Fig. 11C1).

#### DISCUSSION

At the subregional and local scales, sage-grouse were found to be at an increased risk due to future climate change. This conclusion was based on the outputs from the CCVA tools, as well as the evaluation of climate envelopes within sagebrush ecosystems and the patterns of recent droughts. Furthermore, the models show that sage-grouse habitat found within the more xeric ARTRW sagebrush ecosystems are at a higher risk across the region than those for the higher-elevation ARTRV. This finding is consistent with Bradley (2009). At the local scale, risk for the two PACs differed, with Sheeprock at a higher risk, compared to Strawberry. We predicted higher risk for Sheeprock, due to the extreme loss of suitable sagebrush climate, and an increase in conifer and BRTE climate envelopes. Furthermore, Sheeprock had more area impacted by the additional stressors and is more geographically isolated (Fig. 1). Although the Strawberry habitat is not without predicted risk due to future climate changes, the assessment shows much less impact. Additionally, the Strawberry habitat PAC's predicted risk is much more localized compared to Sheeprock. Strawberry is also currently better connected to other occupied sage-grouse habitats, potentially providing additional resilience in the event of a future disturbance. Connectivity to other suitable sage-grouse habitat and populations allows for higher genetic diversity that could lead to an increased adaptive capacity to climate change

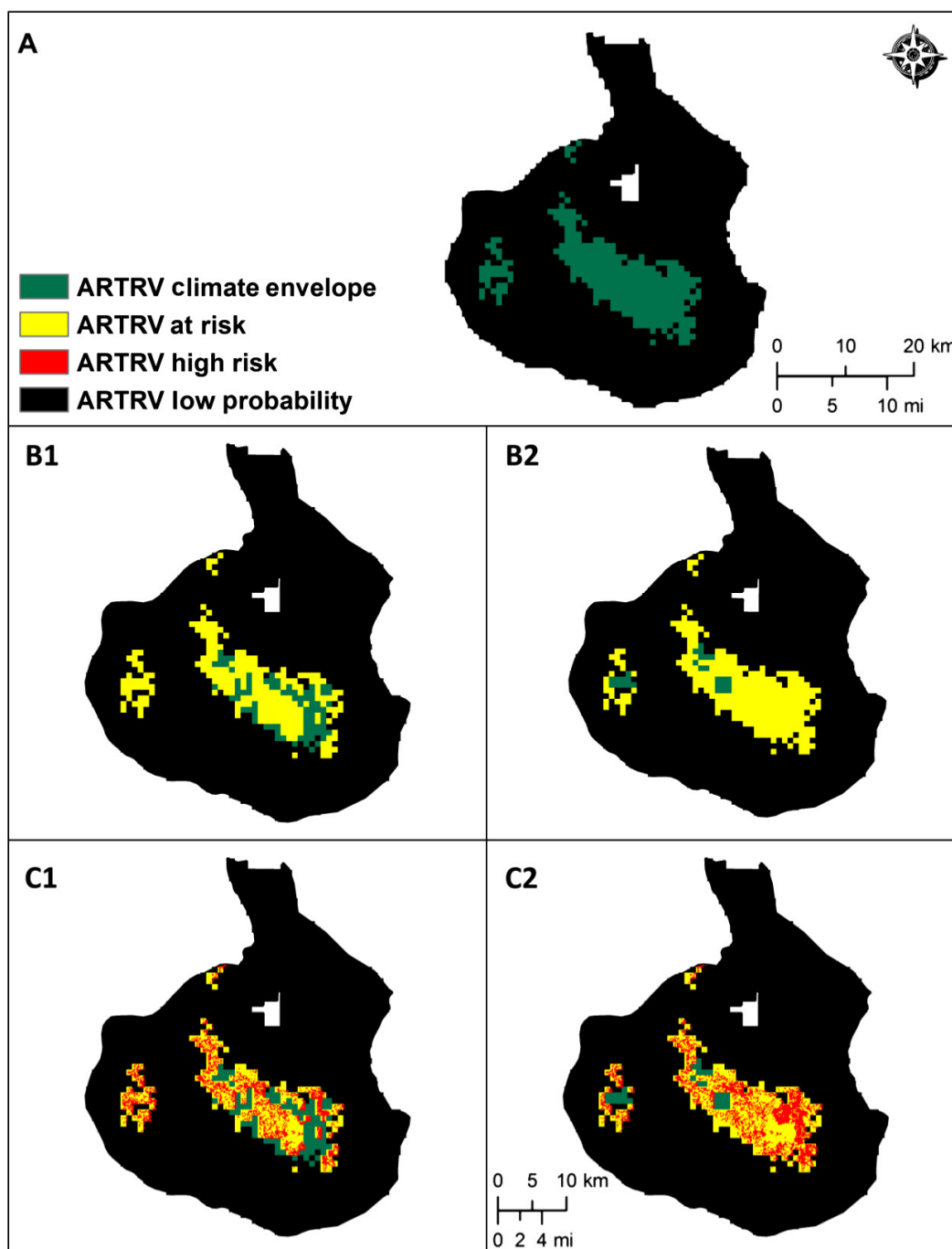


Fig. 8. Sheeprock Priority Area for Conservation. (A) Reference ARTRV climate envelope. (B1, B2) Compared to the reference, the future (2050) ARTRV climate envelope is shown decreasing with increased climate envelopes for conifer (B1) and BRTE (B2) (shown in yellow). (C1, C2) Compared to the reference, the future (2050) ARTRV climate envelope is shown decreasing with increased climate envelopes for conifer (C1) and BRTE (C2) (shown in yellow), and an additional stressor present in areas shown in red (high risk).



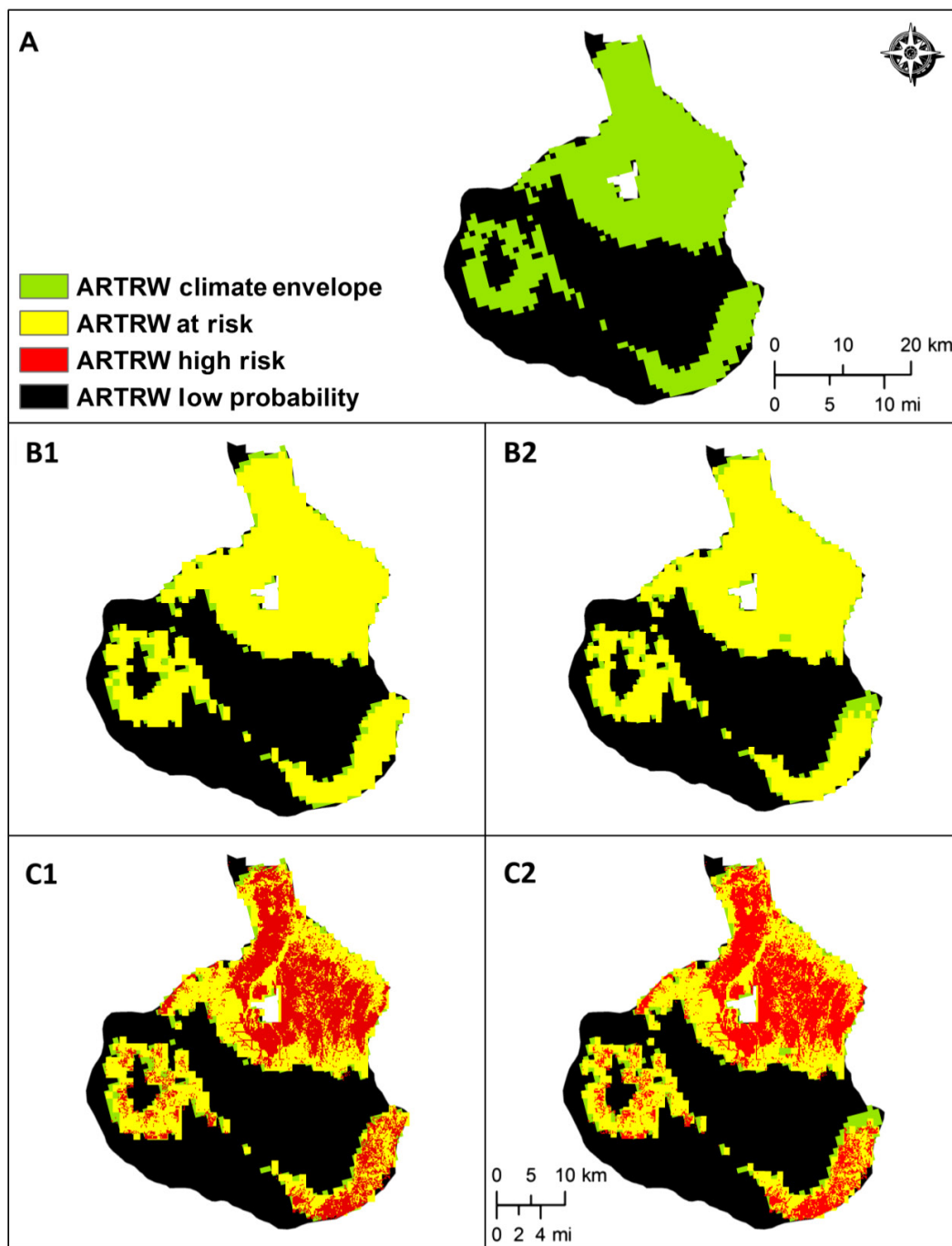


Fig. 9. Sheeprock Priority Area for Conservation. (A) Reference ARTRW climate envelope. (B1, B2) Compared to the reference, the future (2050) ARTRW climate envelope is shown decreasing with increased climate envelopes for conifer (B1) and BRTE (B2) (shown in yellow). (C1, C2) Compared to the reference, the future (2050) ARTRW climate envelope is shown decreasing with increased climate envelopes for conifer (C1) and BRTE (C2) (shown in yellow), and an additional stressor present in areas shown in red (high risk).

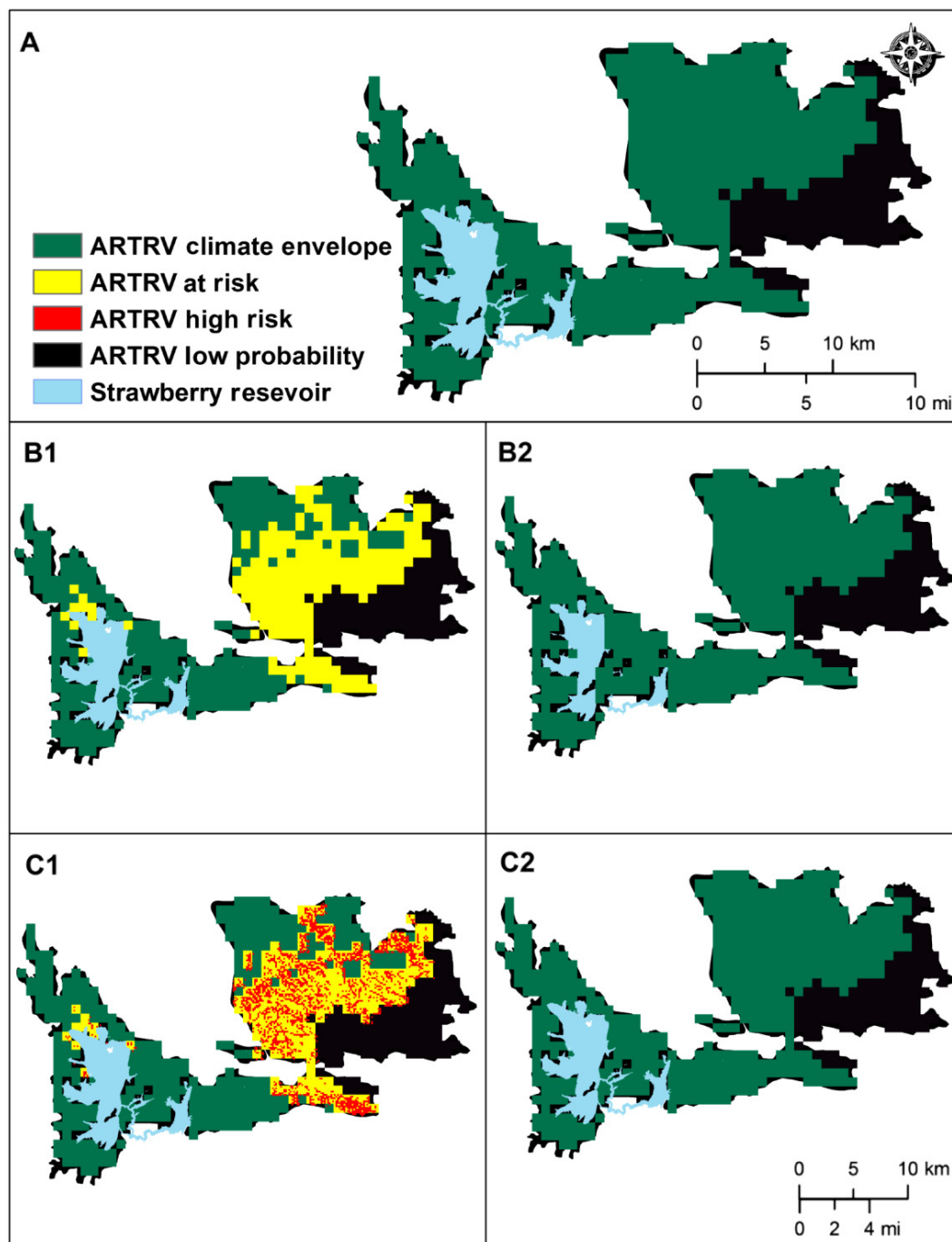


Fig. 10. Strawberry Priority Area for Conservation. (A) Reference ARTRV climate envelope. (B1, B2) Compared to the reference, the future (2050) ARTRV climate envelope is decreased with increased climate envelope for conifer (B1) (shown in yellow), and no predicted change for BRTE (B2). (C1) Compared to the reference, the future (2050) ARTRV climate envelope is decreased with increased climate envelope for conifer (shown in yellow) and an additional stressor present in areas shown in red (high risk). (C2) Compared to the reference, the future (2050) ARTRV climate envelope is decreased with no predicted change for BRTE.

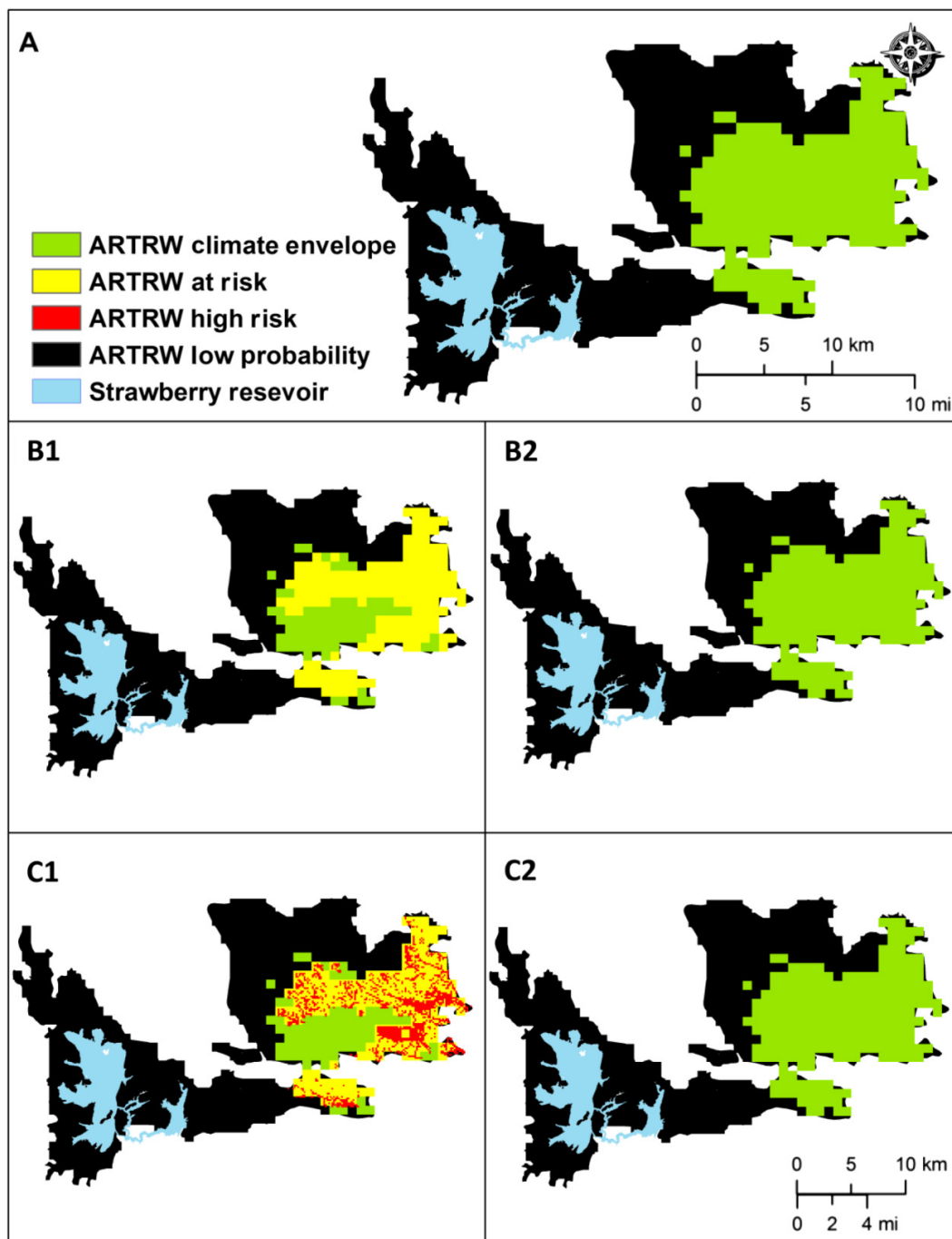


Fig. 11. Strawberry Priority Area for Conservation. (A) Reference ARTRW climate envelope. (B1, B2) Compared to the reference, the future (2050) ARTRW climate envelope is decreased with increased climate envelope for conifer (B1) (shown in yellow), and no predicted change for BRTE (B2). (C1) Compared to the reference, the future (2050) ARTRW climate envelope is decreased with increased climate envelope for conifer (shown in yellow) and an additional stressor present in areas shown in red (high risk). (C2) Compared to the reference, the future (2050) ARTRW climate envelope is decreased with no predicted change for BRTE.



(Beever et al. 2015). Furthermore, connectivity to nearby suitable habitat may increase the chances of sage-grouse returning to the area after recovery from a disturbance, such as a fire. Although sage-grouse and their habitats were used as an example, the presented framework is applicable across other habitats and spatial scales.

Understanding drought periodicity and intensity provides insight into how sage-grouse overall fitness will be affected in future by warmer and drier climates. Droughts can reduce the vegetation cover of nests, the availability and quality of food for chicks and hens during spring brood rearing, and have coincided with declining sage-grouse populations across much of their range (Connelly et al. 2000). Sage-grouse have persisted in the west despite a long history of widespread droughts (Fig. 7), indicating that sage-grouse and their habitats have some adaptive capacity to cope with warmer and drier climates. However, Aldridge et al. (2008) found that past extirpation of sage-grouse in the United States was higher in areas that had three or more severe droughts per decade. Much of the sage-grouse habitat in the study region has experienced such events (Fig. 7). Additional work is needed to determine how long sage-grouse can maintain persistent populations under drier conditions as predicted by current climate models and in the presence of additional modern stressors.

Our risk assessment models integrated several key habitat variables that decrease the adaptive capacity of sage-grouse to climate change. These included fire regimes, conifer encroachment, invasive annual grasses, and anthropogenic impacts. Although these variables interact with each other and climate change, they independently represent additional forces that could impede sage-grouse ability to adapt. Furthermore, they are factors that management can address to possibly reduce future effects, despite a changing climate.

Although fire is a natural component of sagebrush ecosystems, increases in fire frequency, intensity, or extent can have detrimental effects on sage-grouse habitat (Knick et al. 2011). Shortened fire return intervals have been identified as a major threat to sage-grouse and their habitats (USFS 2013). Fire frequencies on xeric sites (e.g., Sheeprock), dominated by Wyoming big sagebrush (ARTRW), are influenced by the

incursion of highly flammable invasive annual species into these systems. These result in increased fire periodicity and extent that results in the loss of sagebrush and in turn, provides a positive feedback for more frequent and larger fire events (e.g., USFWS 2010, Chambers et al. 2013, 2014). This pattern is clearly seen in the Sheeprock PAC. Even when current fires do not increase invasive species abundance, sagebrush postfire recovery may require many decades to return to preburn conditions (Baker et al. 1976, Baker 2006, Beck et al. 2009, Hess and Beck 2012, Nelson et al. 2014). Sagebrush cover recommended for successful sage-grouse nesting has been shown to take over 20 yr, postfire in ARTRV-dominated systems (Nelle et al. 2000).

During the past century, various species of native conifer have encroached upon sagebrush ecosystems throughout the western United States. Expansions of pinyon-juniper woodlands, represented here as various combinations of two-needle (PIED) and single-needle (PIMO) pinyon pines and Utah (JUOS), and western (JUOC) junipers have had major impacts on sagebrush steppe ecosystems, and particularly, in the Great Basin and Colorado Plateau. These woodlands currently occupy more than 19 million ha in the Intermountain West (Davies et al. 2011). By some estimates, approximately 90% of current pinyon-juniper woodland was intact sagebrush steppe prior to European settlement (Miller et al. 2000, Davies et al. 2011). Pinyon-juniper woodlands impact sagebrush ecosystems by reducing sagebrush density and cover (Bates et al. 2005, Weisberg et al. 2007), altering hydrologic processes (Petersen and Stringham 2008), and impacting herbaceous understory composition (Davies et al. 2011). Increased tree cover and the subsequent decline in sagebrush is considered a critical factor in the long-term decline of sage-grouse populations (e.g., Connelly et al. 2004, Aldridge et al. 2008, USFWS 2010). The negative relationship between sage-grouse and conifer encroachment affects all life stages (i.e., nesting, brood rearing, wintering; Doherty et al. 2008, Atamian et al. 2010). Baruch-Mordo et al. (2013) found that sage-grouse can experience population impacts at very low levels of juniper encroachment, and suggested that sage-grouse abandon leks (breeding grounds) when conifer cover exceeds 4%. In addition to habitat

degradation, conifers that have encroached into sagebrush ecosystems add additional perching sites for avian predators of sage-grouse.

Exotic plants, in particular invasive annual grasses, negatively impact sagebrush communities across a broad array of ecological conditions (D'Antonio and Vitousek 1992, Davies et al. 2011). Cheatgrass (*Bromus tectorum* L.; BRTE) has invaded many ecosystems in the western United States, impacting perennial plant communities and changing sagebrush landscapes (Brooks et al. 2004, Chambers et al. 2007a). Invasive species, such as BRTE, impact sagebrush communities by introducing highly flammable fine fuels that affect fire regimes by lengthening the fire season and increasing fuel continuity. This results in more frequent and larger fires. These changes to the fire regime, combined with increased competition for soil moisture during perennial seedling establishment, decrease the ecological extent, pattern, structure, and function of sagebrush communities (Knick and Rotenberry 1997) and result in annual grassland communities, often devoid of native sagebrush. The outcome of annual grass monocultures is impairment and loss of winter habitats and decreased nesting, brood-rearing success, and survival for sage-grouse (Blomberg et al. 2012, Knick et al. 2013). Management of annual grass invasions is difficult and expensive. However, models, such as the ones presented here, could be used to prioritize areas within PACs to focus management resources.

Anthropogenic impact is a broad category that refers to a range of different stressors. In some cases, impacts are direct, such as land conversion or infrastructure (roads, buildings, power lines, etc.). For example, roads can cause mortality as well as have negative effects on lek attendance and nest site selection (Braun et al. 2002, Lyon and Anderson 2003). Other forms of human impacts may be more difficult to assess. Examples include fire suppression, energy development, recreational activities, improper grazing, over-hunting, noise pollution, and unintended predator assistance.

Federal land management agencies have begun incorporating CCVAs as an important component in the management and conservation of landscapes. For example, the Forest Service's 2012 Planning Regulations require the inclusion of climate change analyses in forest planning and

monitoring efforts (USDA 2012). The National Roadmap for Responding to Climate Change (USDA 2011) further includes guidance to assist managers in analyzing and incorporating the potential effects of climate change in long-term conservation planning and management efforts. Mawdsley et al. (2009) reviewed the climate change management adaption plans across several continents and found that managers already have many tools suitable to address climate change. However, they noted that these tools would have to be applied in novel ways. Climate change vulnerability assessments, such as those discussed in the introduction, use expert opinion to determine the species vulnerability. The model framework presented here can assist decision makers by integrating many complex interactions, placing vulnerability into a spatial context, and providing a flexible model that managers could modify based on local knowledge. Data to conduct these analyses are readily available to managers at low cost, and the outcomes of the analyses can inform current and future priorities for conserving and restoring landscapes that are still occupied by sage-grouse. A priority for management agencies should focus on those landscapes that are considered the most important for the long-term conservation of the species that can feasibly be maintained.

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